PCT/GB 00 / 02634

OIPE JC139
OCT 15 2001
PATENT & TRADEMARK OFFICE

PATENTS • DESIGNS
The Patent Office
COPYRIGHT • TRADE MARKS

INVESTOR IN PEOPLE

The Patent Office
Concept House
Cardiff Road
Newport
South Wales
NP10 8QQ

I, the undersigned, being an officer duly authorised in accordance with Section74(1) and (4) of the Deregulation and Contracting Out Act 1994, to sign and issue certificates on behalf of the Comptroller-General, hereby certify that annexed hereto is a true copy of the international application filed on 10 JULY 2000 under the Patent Cooperation Treaty at the UK Receiving Office. The application was allocated the number PCT/GB00/02634.

In accordance with the Patents (Companies Re-registration) Rules 1982, if a company named in this certificate and any accompanying documents has re-registered under the Companies Act 1980 with the same name as that with which it was registered immediately before re-registration save for the substitution as, or the inclusion as, the last part of the name of the words "public limited company" or their equivalents in Welsh, references to the name of the company in this certificate and any accompanying documents shall be treated as references to the name with which it is so re-registered.

In accordance with the rules, the words "public limited company" may be replaced by p.l.c., plc, P.L.C. or PLC.

Re-registration under the Companies Act does not constitute a new legal entity but merely subjects the company to certain additional company law rules.

Signed TARoberts.

Date: 12 September 2001

PCT

REQUEST

The undersigned requests that the present international application be processed according to the Patent Cooperation Treaty.

For receiving Office use only	
International Application No.	PCT/GB 00/02634
International Filing Date	10 JULY 2000 10-07-2000
Name of receiving Office and "PCT International Application"	United Kingdom Patent Office PCT International Application

Applicant's or agent's file reference (if desired) (12 characters maximum)	NS/00060 WO

Box No. I TITLE OF INVENTION

ADAPTIVE BLIND EQUALISER

Box No. II APPLICANT

Name and address: *(Family name followed by given name; for a legal entity, full official designation. The address must include postal code and name of country. The country of the address indicated in this Box is the applicant's State (that is, country) of residence if no State of residence is indicated below.)*

VERTICALBAND LIMITED,
90 FETTER LANE,
LONDON EC4A 1JP.
UNITED KINGDOM

☐ This person is also inventor.

Telephone No.

Facsimile No.

Teleprinter No.

State *(that is, country)* of nationality: ~~BRITISH~~ (GB)

State *(that is, country)* of residence: UNITED KINGDOM (GB)

This person is applicant for the purposes of: ☐ all designated States ☒ all designated States except the United States of America ☐ the United States of America only ☐ the States indicated in the Supplemental Box

Box No. III FURTHER APPLICANT(S) AND/OR (FURTHER) INVENTOR(S)

Name and address: *(Family name followed by given name; for a legal entity, full official designation. The address must include postal code and name of country. The country of the address indicated in this Box is the applicant's State (that is, country) of residence if no State of residence is indicated below.)*

RIESS, EILON,
FLAT 32,
5-3 GLENDOWER PLACE,
LONDON SW7 3DU. GB

This person is:
☐ applicant only
☒ applicant and inventor
☐ inventor only *(If this check-box is marked, do not fill in below.)*

State *(that is, country)* of nationality: ISRAEL (IL)

State *(that is, country)* of residence: UNITED KINGDOM (GB)

This person is applicant for the purposes of: ☐ all designated States ☐ all designated States except the United States of America ☒ the United States of America only ☐ the States indicated in the Supplemental Box

☐ Further applicants and/or (further) inventors are indicated on a continuation sheet.

Box No. IV AGENT OR COMMON REPRESENTATIVE; OR ADDRESS FOR CORRESPONDENCE

The person identified below is hereby/has been appointed to act on behalf of the applicant(s) before the competent International Authorities as: ☒ agent ☐ common representative

Name and address: *(Family name followed by given name; for a legal entity, full official designation. The address must include postal code and name of country.)*

SHINDLER, NIGEL
BATCHELLOR, KIRK & CO.,
102-108 CLERKENWELL ROAD,
LONDON EC1M 5SA. GB

Telephone No. 0207 253 1563

Facsimile No. 0207 253 1214

Teleprinter No.

☐ **Address for correspondence:** Mark this check-box where no agent or common representative is/has been appointed and the space above is used instead to indicate a special address to which correspondence should be sent.

Box No.V DESIGNATION OF STATES

The following designations are hereby made under Rule 4.9(a) *(mark the applicable check-boxes: at least one must be marked)*:

Regional Patent

- [X] **AP** **ARIPO Patent:** GH Ghana, GM Gambia, KE Kenya, LS Lesotho, MW Malawi, SD Sudan, SL Sierra Leone, SZ Swaziland, TZ United Republic of Tanzania, UG Uganda, ZW Zimbabwe, and any other State which is a Contracting State of the Harare Protocol and of the PCT
- [X] **EA** **Eurasian Patent:** AM Armenia, AZ Azerbaijan, BY Belarus, KG Kyrgyzstan, KZ Kazakhstan, MD Republic of Moldova, RU Russian Federation, TJ Tajikistan, TM Turkmenistan, and any other State which is a Contracting State of the Eurasian Patent Convention and of the PCT
- [X] **EP** **European Patent:** AT Austria, BE Belgium, CH and LI Switzerland and Liechtenstein, CY Cyprus, DE Germany, DK Denmark, ES Spain, FI Finland, FR France, GB United Kingdom, GR Greece, IE Ireland, IT Italy, LU Luxembourg, MC Monaco, NL Netherlands, PT Portugal, SE Sweden, and any other State which is a Contracting State of the European Patent Convention and of the PCT
- [X] **OA** **OAPI Patent:** BF Burkina Faso, BJ Benin, CF Central African Republic, CG Congo, CI Côte d'Ivoire, CM Cameroon, GA Gabon, GN Guinea, GW Guinea-Bissau, ML Mali, MR Mauritania, NE Niger, SN Senegal, TD Chad, TG Togo, and any other State which is a member State of OAPI and a Contracting State of the PCT *(if other kind of protection or treatment desired, specify on dotted line)* . . . .

National Patent *(if other kind of protection or treatment desired, specify on dotted line)*:

- [X] **AE** United Arab Emirates
- [X] **AL** Albania . . . .
- [X] **AM** Armenia . . . .
- [X] **AT** Austria . . . .
- [X] **AU** Australia . . . .
- [X] **AZ** Azerbaijan
- [X] **BA** Bosnia and Herzegovina . . . .
- [X] **BB** Barbados
- [X] **BG** Bulgaria . . . .
- [X] **BR** Brazil . . . .
- [X] **BY** Belarus . . . .
- [X] **CA** Canada
- [X] **CH and LI** Switzerland and Liechtenstein
- [X] **CN** China . . . .
- [X] **CR** Costa Rica . . . .
- [X] **CU** Cuba . . . .
- [X] **CZ** Czech Republic . . . .
- [X] **DE** Germany . . . .
- [X] **DK** Denmark . . . .
- [X] **DM** Dominica
- [X] **EE** Estonia . . . .
- [X] **ES** Spain . . . .
- [X] **FI** Finland . . . .
- [X] **GB** United Kingdom
- [X] **GD** Grenada
- [X] **GE** Georgia . . . .
- [X] **GH** Ghana . . . .
- [X] **GM** Gambia
- [X] **HR** Croatia . . . .
- [X] **HU** Hungary . . . .
- [X] **ID** Indonesia
- [X] **IL** Israel . . . .
- [X] **IN** India . . . .
- [X] **IS** Iceland
- [X] **JP** Japan . . . .
- [X] **KE** Kenya . . . .
- [X] **KG** Kyrgyzstan . . . .
- [X] **KP** Democratic People's Republic of Korea . . . .
- [X] **KR** Republic of Korea . . . .
- [X] **KZ** Kazakhstan . . . .
- [X] **LC** Saint Lucia
- [X] **LK** Sri Lanka
- [X] **LR** Liberia
- [X] **LS** Lesotho . . . .
- [X] **LT** Lithuania
- [X] **LU** Luxembourg
- [X] **LV** Latvia
- [X] **MA** Morocco . . . .
- [X] **MD** Republic of Moldova . . . .
- [X] **MG** Madagascar . . . .
- [X] **MK** The former Yugoslav Republic of Macedonia . . . .
- [X] **MN** Mongolia
- [X] **MW** Malawi . . . .
- [X] **MX** Mexico . . . .
- [X] **NO** Norway . . . .
- [X] **NZ** New Zealand . . . .
- [X] **PL** Poland . . . .
- [X] **PT** Portugal . . . .
- [X] **RO** Romania
- [X] **RU** Russian Federation . . . .
- [X] **SD** Sudan
- [X] **SE** Sweden
- [X] **SG** Singapore
- [X] **SI** Slovenia . . . .
- [X] **SK** Slovakia . . . .
- [X] **SL** Sierra Leone . . . .
- [X] **TJ** Tajikistan . . . .
- [X] **TM** Turkmenistan . . . .
- [X] **TR** Turkey . . . .
- [X] **TT** Trinidad and Tobago . . . .
- [X] **TZ** United Republic of Tanzania
- [X] **UA** Ukraine . . . .
- [X] **UG** Uganda . . . .
- [X] **US** United States of America . . . .
- [X] **UZ** Uzbekistan . . . .
- [X] **VN** Viet Nam . . . .
- [X] **YU** Yugoslavia . . . .
- [X] **ZA** South Africa . . . .
- [X] **ZW** Zimbabwe . . . .

Check-boxes reserved for designating States which have become party to the PCT after issuance of this sheet:

- [ ] . . . .
- [ ] . . . .

Precautionary Designation Statement: In addition to the designations made above, the applicant also makes under Rule 4.9(b) all other designations which would be permitted under the PCT except any designation(s) indicated in the Supplemental Box as being excluded from the scope of this statement. The applicant declares that those additional designations are subject to confirmation and that any designation which is not confirmed before the expiration of 15 months from the priority date is to be regarded as withdrawn by the applicant at the expiration of that time limit. *(Confirmation (including fees) must reach the receiving Office within the 15-month time limit.)*

PCT/GB 00/02634

Box No. VI PRIORITY CLAIM ☐ Further priority claims are indicated in the Supplemental Box.

Filing date of earlier application *(day/month/year)*	Number of earlier application	Where earlier application is: national application: country	regional application:* regional Office	international application: receiving Office
item (1)				
item (2)				
item (3)				

☐ The receiving Office is requested to prepare and transmit to the International Bureau a certified copy of the earlier application(s) *(only if the earlier application was filed with the Office which for the purposes of the present international application is the receiving Office)* identified above as item(s):

* *Where the earlier application is an ARIPO application, it is mandatory to indicate in the Supplemental Box at least one country party to the Paris Convention for the Protection of Industrial Property for which that earlier application was filed (Rule 4.10(b)(ii)). See Supplemental Box.*

Box No. VII INTERNATIONAL SEARCHING AUTHORITY

Choice of International Searching Authority (ISA) *(if two or more International Searching Authorities are competent to carry out the international search, indicate the Authority chosen; the two-letter code may be used)* :

ISA /

Request to use results of earlier search; reference to that search *(if an earlier search has been carried out by or requested from the International Searching Authority)*:

Date *(day/month/year)* Number Country *(or regional Office)*

Box No. VIII CHECK LIST; LANGUAGE OF FILING

This international application contains the following **number of sheets**:

request	:	3
description (excluding sequence listing part)	:	15
claims	:	2
abstract	:	1
drawings	:	2
sequence listing part of description	:	
Total number of sheets	:	23

This international application is **accompanied by the item(s) marked below**:

1. ☐ fee calculation sheet
2. ☐ separate signed power of attorney
3. ☐ copy of general power of attorney; reference number, if any:
4. ☐ statement explaining lack of signature
5. ☐ priority document(s) identified in Box No. VI as item(s):
6. ☐ translation of international application into (language):
7. ☐ separate indications concerning deposited microorganism or other biological material
8. ☐ nucleotide and/or amino acid sequence listing in computer readable form
9. ☐ other *(specify)*:

Figure of the drawings which should accompany the abstract:

Language of filing of the international application:

Box No. IX SIGNATURE OF APPLICANT OR AGENT

Next to each signature, indicate the name of the person signing and the capacity in which the person signs (if such capacity is not obvious from reading the request).

SHINDLER, NIGEL 10TH JULY 2000

For receiving Office use only

1. Date of actual receipt of the purported international application: 10 JULY 2000 10-07-2000	2. Drawings: ☐ received: ☐ not received:
3. Corrected date of actual receipt due to later but timely received papers or drawings completing the purported international application:	
4. Date of timely receipt of the required corrections under PCT Article 11(2):	
5. International Searching Authority (if two or more are competent): ISA /	6. ☐ Transmittal of search copy delayed until search fee is paid.

For International Bureau use only

Date of receipt of the record copy by the International Bureau:

"Adaptive Blind Equaliser"

This invention relates to communication channel equalisers, and in particular, to an equaliser which is particularly adapted for use when receiving high-order constellation signals over an ISI channel.

When a signal is transmitted over a communication channel of a normal type which produces "ISI" (Intersymbol interference) or multi-path interference, the effect of the interference is increased considerably, for high order constellations. In our copending British patent application no. 9926167.9, we have described a method of enabling high order constellation communication, without lowering the symbol rate, by evaluating the channel characteristics without the use of any training sequence.

The method of high order constellation signal transmission through an ISI channel, according to the above mentioned prior application, involves identifying "reliable symbols", that is to say, symbols which are closer to their received constellation point free from ISI noise effect, than to any other received constellation point.

In order to implement efficiently, a signal communication system of the kind described above, it is appropriate to provide an equaliser and an adaptive estimator for the ISI coefficients. Accordingly, one aspect of the present invention provides a receiver system for an ISI channel, comprising a "mismatch equaliser" having two main inputs, one of which is supplied with the received signal, whilst the other is supplied with ISI/multipath coefficients comprising the output of an adaptive estimator, having one input which is supplied with the received signal and another input which is supplied with output decisions from the equaliser.

By the term "mismatch equaliser" we mean an equaliser which can work even without knowledge of the ISI/multi-path coefficients.

Preferably, the adaptive estimator operates in a similar way to that described in our above mentioned copending application no. 9926167.9, in which reliable symbols are extracted and utilised in order the derive the ISI channel characteristics. This is preferably done by means of a weighting matrix which attaches a high weight for each reliable symbol, and a low weight for a non-reliable symbol.

The invention also extends to a method of process of trellis equalisation, for an ISI/multipath channel when high order constellation communication is used, which comprises the steps of:

1) Identifying an initial "reliable symbol" in the received signal;
2) Setting an initial value for the ISI coefficients;
3) Estimating the sequence of at least N length prior symbols, where N is the selected length of the ISI channel window;
4) Identifying the most likely branch or set of branches of the trellis following the reliable symbol;
5) Using the branch or set of branches to determine the next individual symbol or symbol path and to provide a refined estimate of the ISI coefficients;
6) Moving the channel window forward so as to include a new sequence of N symbols and repeating the process with the new sequence of symbols and the refined estimate of the ISI.

Although a training sequence is not required for the method to work, there are cases in which a single training symbol can be used as a reliable symbol, purely to initialise the trellis.

Typically the initial value is a guess of the ISI coefficients which may for example simply comprise an all zero vector of length N.

In an ideal realisation of the process, which would involve "soft detection", considerable computation power would be required, because multiple integrations, involving multiple summations, have to be carried out for each branch of the trellis. Accordingly the branch weight calculation may be replaced with a "hard detection" approach by finding the branch closest to the average of the rescattered received signal, as will be described in more detail below.

The present invention also extends to a mismatch equaliser using the above method of trellis equalisation, and to a receiver system incorporating such a mismatch equaliser, the equaliser having two main inputs, one of which is supplied with the received signal, whilst the other is supplied with ISI/multipath coefficients comprising the output of an adaptive estimator, whose input is supplied with output decisions from the equaliser as well as the received signal.

Thus in a practical embodiment the mismatch equaliser is located in the receiver, for example just after a matched filter, after transforming the analogue signal into its

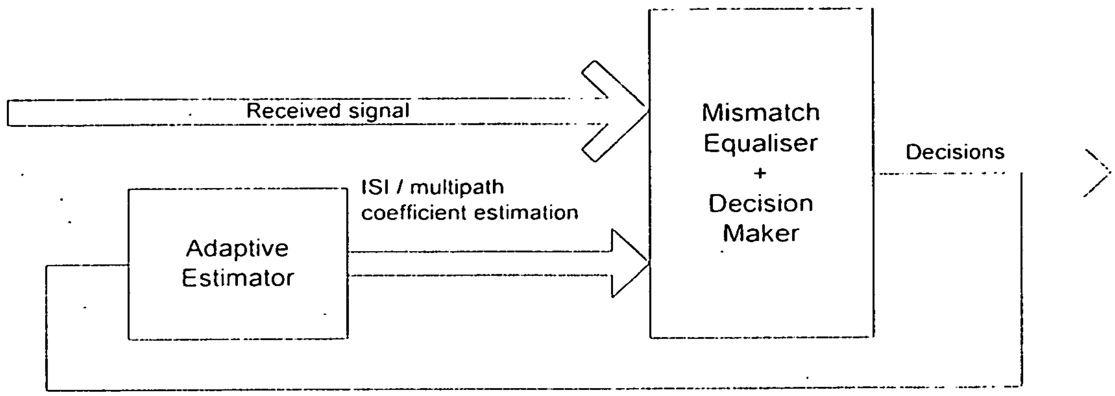
base-band digital form. The input is connected to the output of the matched filter and produces at its output the decision on the transmitted symbols and/or the transmitted bits, which can then be further processed by the other receiver components such as the decoder or can be used as the final output of the receiver. Although the equaliser and the estimator can be used as individual components since they do not depend on each other, they are preferably used together so as to provide maximum performance with minimal complexity.

The present invention accordingly provides the following advantages:

1. Fast and precise equalisation and estimation for up to severe ISI/multipath channel, even beyond the "binary open eye" limit, when high order constellation is used.
2. There is no theoretical limit to the size of the constellation. Simulation results confirm successful operation of up to and including 4096 QAM, 600% higher than QPSK (4 QAM).
3. The system operates successfully even for very low SNR. Simulation results confirm successful operation for SNR as low as 4dB difference between constellation points.
4. The number of symbols that is required depends mainly on the constellation size, but also on the initial guess of the coefficients, the SNR and the level of ISI/multipath. Typical numbers for severe ISI/multipath channel with relative low SNR when 64 QAM is used is around 2000-3000 symbols. Under the same conditions but using 1024 QAM requires about 7000 symbols. In the case of DTV and 3G mobile phone channels this represents a short delay of up-to the order of several milliseconds (**only just for the first symbols, the remainder will not be subject to any delay).**
5. The system successfully operates even for very fast moving channel, up to changes within 100 symbols, which represent for a 3G mobile phone, channel variation in the order of few dozen of microseconds, i.e. is an extremely fast moving channel. Contrary to the case in which the channel is constant the initial processed received data (e.g. the first couple of milliseconds) cannot be recovered.

The system can be describe by the schematic shown in Figure 1.

The Receiver system



The equaliser has two main inputs, the received data stream and the range of each coefficient of the ISI/multipath channel that is being fed by the adaptive estimator. The adaptive estimator has for its inputs the decisions that are based on the equaliser as well as the received signal.

Estimator:

The operation of the adaptive estimator is preferably similar to the one that is presented in our copending British patent application no. 9926167.9. In the present case the number of reliable symbols that are used in the estimation process is much larger compared with the number that was considered in that application because of the use of trellis tree. The weighting matrix attaches a high weight for a reliable symbol and a low weight for a non-reliable symbol.

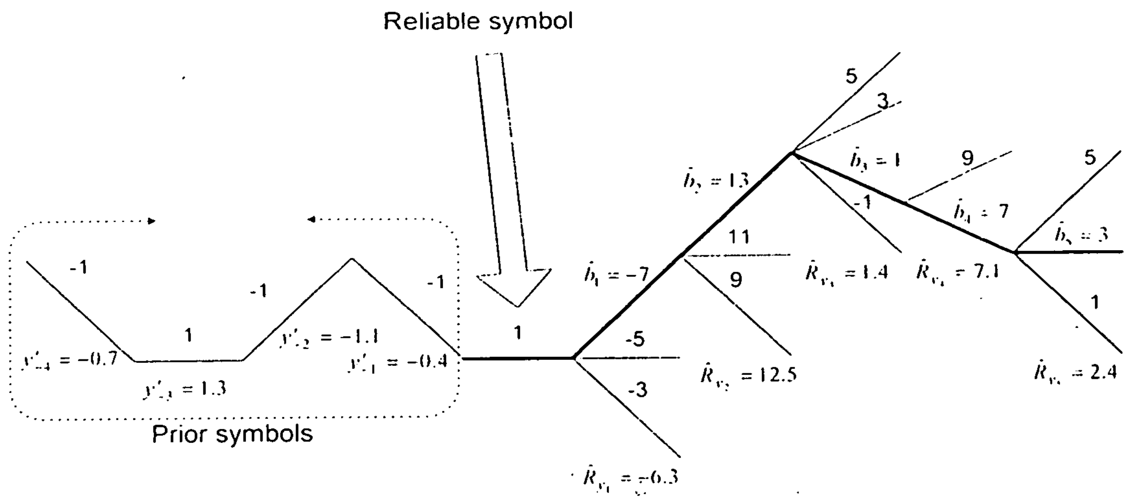
Equaliser:

The equaliser may be realised in two versions "optimal" ("soft detection") and a "close to optimal" ("hard detection") practical equaliser. The difference between the two versions is in the number of calculations for each branch in the trellis. For the vast majority of communication applications the practical close to optimal equaliser will be adequate.

The schematic of Figure 2 presents the equalisation and decision making process for both versions.

Trellis Equalisation and Hard decision

256QAM / 4 coefficients length Multipath channel



(The symbols in the schematic and the equations mentioned in this summary are explained in the detailed technical description which follows).

First an initial reliable symbol has to be identified using the method presented in our above mentioned copending application. Then its N length prior symbols sequence has to be estimated, where N is the assumed length of the ISI/multipath channel window. In the present case the symbols are simply chosen according to their nearest constellation points. After this stage the two versions of the equaliser follow two different paths:

Practical close to optimal equaliser: (Hard Detection)

After establishing the reliable symbol and the prior symbols the system decides on the next symbol according to Eq. 14 & 15 (below), based on an expected ISI coefficient range. Then, the prior symbols window moves one step forwards, thus dropping the first symbol and adding the newly decided symbol, and thereafter by using the next received signal and the new prior symbols sequence in Eq. 14 & 15 the next symbol can be determined, and so on and so forth. After gathering "enough" data points, in which "enough" depends on the actual application requirement, the decision based on the equaliser are fed into the adaptive estimator that produce then its new estimation / the new range for each coefficient. In fact, if required, the estimation can be performed after each step of the symbol detection.

Optimal equaliser (Soft Detection):

After establishing the reliable symbol and the prior symbols the equaliser decides first which of the branches are participating as candidates for the next need to be decided symbol, by using Eq.12 & 13 i.e. taking into account the expected ISI range. Then for each chosen branch the probability is calculated by using Eq.10 or 11 (depending whether the channel gain is known (Eq.11) or not (Eq.10)). Thereafter the process continues as a regular trellis equalisation, where for each step in time the participating branches are determined according to Eq. 12 & 13 and their probabilities are calculated according to Eq. 10 or 11. The decision on the symbols requires a delay of N, the length of the ISI/multipath channel (typical numbers are 2-10 symbols which practically means zero time delay for the vast majority of communication applications).

It will therefore be appreciated that this invention provides a number of significant improvements over prior systems, because of

1. The whole concept and the mechanism of the use of the trellis and the reliable symbols for equalisation, and requiring just a range for each coefficient.
2. The combination of the equaliser and the estimator.
3. The two metrics/probabilities calculation (optimal and sub-optimal).
4. The participating branches determination.
5. The convergence of the range of ISI which produces a progressively greater number of reliable symbols.
6. The system of the present invention is suitable for a wide variety of communication technologies, including various different types of networks including:
7. (a) x-DSL (DMT) and x-DSL (CAP)
8. (b) Mobile telephone (wireless) networks: 2G and 3G, that is to say:

   GSM, 2000CDMA, W-CDMA (UMTS), EDGE

   It may of course be employed both in handsets and base stations.

   (c) Digital TV: COFDM (DVB)

   It may also be used in a variety of transmission media including fibre optics.

Some embodiments of the invention are described in more detail, by way of example, in the attached technical paper.

VerticalBand

Equalisation and adaptive estimation under mismatch channel parameters condition when high-order constellation is used, based on "Reliable Symbols method"

Eilon Riess

1. Introduction:

Bandwidth constraints motivate the use of high-order constellation transmission, where higher bit-rate transmission is achieved when using the same limited bandwidth. As is shown in [1], the use of high-order constellation accentuates the Intersymbol Interference (ISI) / multipath effect, with the constellation order acting, in effect, as an amplifier on the ISI / multipath level.

Blind equalisation therefore becomes a very difficult, if not impossible, task when a high-order constellation is used [2],[3]. Even more, various existing and future data communication channels are time varying (e.g mobile phone, terrestrial DTV) and/or produce poor signal reception in which in turn results in a low SNR.

In [1] an overview on the existing blind equalisation techniques is provided and a new method, which is called the 'Reliable Symbols method', is presented. This method makes possible successful parameter estimation, adaptive parameter estimation and equalisation when using high-order constellation communication in the presence of high levels of ISI.

In this paper we present a mismatch-able equalisation technique when high-order constellation is used, based on the 'Reliable Symbols method'. Mismatch equalisation refers to the situation in which the equaliser do not have as an input the exact value of the ISI/multipath coefficients, but rather, the equaliser is provided only with a range for each parameter. As an example this situation exists in a time varying channel and in the case in which low SNR results with poor estimation of the ISI/multipath coefficients.

In addition we present an adaptive estimation technique, when high-order constellation is used, based on the 'Reliable Symbols method' and on the decisions made by the mismatch–able equaliser. Finally we discuss a receiver system that is a combination of the adaptive estimator and the mismatch-able equaliser. It is shown that this system provides reliable high-order constellation communication under the condition: a) high level of ISI/multipath, greater than the binary open eye limit [1,2], b) up-to a long ISI/multipath window and c) for fast time varying channels and/or for low SNR situation.

The system does not require extensive computation nor long received data length for its processing, which makes it applicable for most communication applications and systems. Simulation results demonstrate the performance of the equaliser, the adaptive estimator and the combined receiver system.

The paper is divided into six sections: In Section 2 the mismatch-able equaliser is presented according to its different features. Section 3 presents the combined receiver system, adaptive estimation and equalisation.

2. Equaliser:

Successful signal detection requires the use of an equaliser when the data passes through an ISI/multipath channel. As shown in [1] high-order constellation communication when the signal passes through a given ISI/multipath channel results in a very high level of noise, dozens or even hundreds of times higher compared to low-order constellation communication. Since the equalisation process is based on the knowledge of the channel parameters, the ISI/multipath coefficients, even a minor distance from the correct coefficients results with unreliable data communication for existing communication system. The error, the distance from the correct ISI/multipath coefficients, can be the result of one or more of the following situations:

a. The ISI/multipath coefficients were known to the equaliser in some point of time, but had drifted away because of the time variation characteristics of the channel (e.g. mobile phone).
b. The ISI/multipath coefficients are not known to the equaliser, and the estimation of them is not sufficient, as a result of a low SNR (e.g. poor reception of a received signal, low-power communication) and/or a short received data sequence that is required in real time systems.
c. The average value of the ISI/multipath coefficients are known to the receiver, but rather than being steady the coefficients themselves are noisy (e.g. hardware channels such as routers, copper lines).

We present an equaliser that enables the use of high-order constellation transmission when the signal passes through an ISI/multipath channel that is based on the following: 1) The reliable symbols that are hidden inside the received data stream; 2) trellis demodulation; 3) a new metric calculation method.

2.1 The components:

The proposed equaliser is based on trellis demodulation. First of all the starting point in the trellis, the anchor, needs to be found. After receiving a predetermined number of data points a reliable symbol is identified, using the method described in [1]. The necessary number of data points is determined according to the minimum number of received data points that is required to secure at least one reliable symbol, which is determined according to the probability to find a reliable symbols [1]. Then, each surrounding symbol is chosen according to the minimum distance from the received signal. After this two stages the equaliser has as an anchor the first correct symbol and in addition the equaliser has a good idea about the surrounding symbols. To proceed with the equalisation process the trellis equalisation requires calculating the weight of each branch in the trellis. We use the maximum likelihood detection, thus,

$$\mathbf{X}_{ML} = \{\mathbf{X} : \max P_r(\mathbf{Y}/\mathbf{X}\} \qquad (1)$$

where $\mathbf{X}$ contains all possible symbol-paths in the trellis, $\mathbf{Y}$ the re-scattered received signal according to $\mathbf{X}$ and the channel ISI/multipath coefficients,

$$\mathbf{Y} = \left\{ y'_n - \sum_{i=1}^{N} x_{n-i} \cdot ISI \right\}_{n=1}^{M} \qquad (2)$$

where y'_n is the n received signal, $\{x_{n-i}\}_{n=1}^{N}$ the previous N symbols in the assumed path and M the length of the trellis. We assume here, without the losing generality, a one side ISI/multipath channel, since a two side ISI/multipath channel can be described as a one side by introducing a delay mechanism.

In our case the ISI/multipath coefficients are not known and for the purpose of generality let us assume that the channel gain is not known as well (in [2] a fast and sufficient way to recover the channel gain is presented). However, an integration on the joint probability, $P_R(\mathbf{Y}, \mathbf{ISI}/\mathbf{X})$, provides,

$$P_r(\mathbf{Y}/\mathbf{X}) = \int_{\mathbf{ISI}_{N+1}} P_R(\mathbf{Y}, \mathbf{ISI}/\mathbf{X}) \qquad (3)$$

where $\int_{\mathbf{ISI}_{N+1}}$ represents an N+1, the length of the ISI/multipath window plus one, multiple integrations according to the N+1 coefficients, and $\mathbf{ISI} = (ISI_0, ISI_1, ..., ISI_N)$ where ISI_0 is the channel gain coefficient .

Using Baye's Rule, it is obtained that,

$$P_r(\mathbf{Y}/\mathbf{X}) = \int_{\mathbf{ISI}_{N+1}} P_R(\mathbf{Y}/\mathbf{ISI},\mathbf{X}) \cdot P_R(\mathbf{ISI}) \qquad (4)$$

The maximum likelihood detection for a general ISI/multipath mismatch situation can now be carried out based on Eq.4.

In the situation in which there is no knowledge about the probability distribution of the ISI/multipath coefficients, $P_R(\mathbf{ISI})$, we assume a uniform probability distribution over a predetermined range. In addition let us assume that the received signal is not statistical correlated in time, thus:

$$P_r(\mathbf{Y}/\mathbf{ISI},\mathbf{X}) = \prod_n P_r(y_n/\mathbf{ISI},\mathbf{X}) \qquad (5)$$

since the assumption is a one side ISI/multipath channel and taking account the length, N, of the ISI/multipath window, Eq.5 becomes,

$$P_r(\mathbf{Y}/\mathbf{X}) = \prod_n P_r(y_n/\mathbf{ISI},\mathbf{X}_n^N) \qquad (6)$$

where $\mathbf{X}_n^N = \{x\}_{n-N}^{n}$; $x \in \mathbf{X}$

Involving Eq.6 into Eq.4 and using the uniform probability distribution over a predetermined range of $P_R(\mathbf{ISI})$, provides the following expression,

$$P_R(\mathbf{Y}/\mathbf{X}) = \int_{\mathbf{ISI}_{N+1}} \prod_n \frac{1}{\left|\mathbf{ISI}^R\right|} \cdot P_r(y_n/\mathbf{ISI},\mathbf{X}_n^N) \qquad (7)$$

where $1/\left|\mathbf{ISI}^R\right|$ is the probability of the ISI/multipath coefficients.

IC is easy to show that the order of integration and the multiplication can be switched, therefore it is obtained that,

$$P_R(\mathbf{Y}/\mathbf{X}) = \prod_n \frac{1}{\prod_i \left|ISI_i^R\right|} \int_{ISI_0^R} \int_{ISI_1^R} \cdots \int_{ISI_N^R} P_R\{y_n/(ISI_0, ISI_1, .., ISI_N), \mathbf{X}_n^N\} \qquad (8)$$

where ISI_i^R is the predetermined range for each ISI/multipath coefficient and $\left|ISI_i^R\right|$ is the range size of each coefficients respectively. Since $\left|ISI_i^R\right|$ does not depend on the assumed symbol sequence it can be dropped for the Maximum likelihood calculation. Therefore, the complete maximum likelihood expression of Eq.8 becomes,

$$\mathbf{X}_{ML} = \left\{ \mathbf{X} : \max\left\{ \prod_n \int_{ISI_0^R} \int_{ISI_1^R} \cdots \int_{ISI_N^R} \frac{1}{\sqrt{2\pi\sigma^2}} e^{-(y_n - \sum_{j=0}^{N} x_{n-j} \cdot ISI_j)^2/2\sigma^2} dISI_0 \cdots dISI_N \right\} \right\} \qquad (9)$$

where σ^2 is the STD of the AWGN.

It is easy to see that the weight $w_{m,n}^N$, in which m is the assumed transmitted symbol path, depends on the prior N-symbol-length path and it is expressed by,

$$w_{m,n}^N = \left\{ \int\limits_{ISI_0^R} \int\limits_{ISI_1^R} \cdots \int\limits_{ISI_N^R} \frac{1}{\sqrt{2\pi\sigma^2}} e^{-(y_n - \sum_{j=0}^{N} x_{n-j}^m \cdot ISI_j)^2/2\sigma^2} dISI_0 \cdots dISI_N \right\} \tag{10}$$

Since the channel gain recovery can be achieved using the method of [2] Eq.10 can be simplified, therefore,

$$w_{m,n}^N = \left\{ \int\limits_{ISI_1^R} \cdots \int\limits_{ISI_N^R} \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\{(y_n - \sum_{j=1}^{N} x_{n-j}^m \cdot ISI_j) - x_n\}^2/2\sigma^2} dISI_1 \cdots dISI_N \right\} \tag{11}$$

where the ISI/multipath coefficients are now normalised according to the channel gain coefficient.

The number of calculations that is involved in each branch weight, $w_{m,n}^N$, increases by an order of magnitude for longer ISI/multipath windows, which for some application is too high. In Section 2.2 a sub-optimal hard-decision practical branch weight with very few calculations is presented.

After having the first point in the trellis and knowing how to calculate the branch metrics, we will now describe the way the trellis tree is used according to the Maximum likelihood approach of Eq.8 for successful equalisation and detection.

2.2 The equaliser:

For a given branch in the trellis, in which the anchor, the reliable symbol is the first branch, a re-scattering range for the next received signal, y_n', is defined as follows,

$$R_{y_n} = y_n' - \sum_{i=1}^{N} x_{n-i}^m \cdot ISI_i^{av} + \left(\sum_{i=1}^{N} \left| x_{n-i}^m \right| \cdot \frac{\left| ISI_i^R \right|}{2} \right) \cdot \{1, -1\} \tag{12}$$

where ISI_i^{av} is the expectation of ISI_i^R and $\left|ISI_i^R\right|$ is the size of the range of ISI_i^R. Let us examine the range in Eq.10. When there is no mismatch the range size, $\left|R_{y_n}\right|$ is nil and it is an increasing function of the size range, $\left|ISI_i^R\right|$, and the absolute level of the prior

assumed symbols, $\{|X_{n-N}|,\ldots,|X_{n-i}|\}$. As described in [1] even in the situation in which high-order constellation is used and the signal passes through an ISI/multipath channel, there is a considerable number of symbols that are reliable, thus they are closer to their associated received constellation points than to any other received constellation point. In this case, in effect, the trellis-based equalisation provides the use of the whole set of the reliable symbols when the correct path is considered and the majority of reliable symbols when a path that is "close" to the correct one is considered. In the case in which there is no knowledge about the ISI/multipath coefficients, so that logical starting point is the all zero length N vector guess, the number of detectable reliable symbols is the same as the case where the reliable symbols are detected through the received signal energies [1,2]. However, on the other hand, when the ISI/multipath coefficients are known every symbol is a reliable symbol. Notice that in our case, in which the trellis tree is used, the reliable symbols are a function of the uncertainty size, the difference of the existing coefficients from the guessed ones, and not the absolute uncertainty. As a result there are more detected reliable symbols for smaller difference between the estimate and existing ISI/multipath coefficients. Since the uncertainty in the ISI/multipath coefficients is according to the range, R_{y_n}, the noise after the re-scattering of the received signal is equal or less to the situation in which there is no "a priori" knowledge about the ISI/multipath range. Based on [1] it is easy to show that the number of reliable symbols among the set of received data points is actually a function of $1/|R_{y_n}|$. The total effect is thus: since the adaptive estimation reduces the range R_{y_n} each further estimation step is more accurate and converges faster as a result of the double effect of 1) the difference between the assumed and true ISI/multipath being smaller and 2) the number of reliable symbols increasing as well.

We will now describe how this property of the range is used in the equalisation process.

After defining the range R_{y_n} the branches that are inside or close to the range borders are considered as possible received symbol candidates, thus

$$h_{n,m} \in [R_{y_n} - \varepsilon(SNR)\ ,\ R_{y_n} + \varepsilon(SNR)] \tag{13}$$

The exact number of candidate symbols that are outside R_{y_n} borders is a function of the SNR, for high SNR fewer points are taken into account and vice versa. Up to 2

symbols in each direction was found to be sufficient even for very low SNRs. Although, the failure to consider all possible branches results in a sub-optimal detection in the presence of AWGN, the decrease in the number of calculations and memory storage for most practical use, outweighs the very small degree of sub-optimality. However, if it is required there is no restriction on the number of candidate branches that can participate.

Since a considerable fraction of the data points are actually reliable symbols, and since a smaller range means a higher number of reliable symbols, it is easy to see, according to Eq.12, that the size of R_{y_n}, $\left|R_{y_n}\right|$, is small for a considerable amount of symbols. This results with a smaller bank of symbols to chose from, thus less calculation and smaller memory size is required. In the same manner as in any trellis demodulation/decoding, each symbol candidate branch weight is calculated and the overall path probability for each path is kept in memory. Since the ISI/multipath influences up to N symbols, a decision can be made after N steps in the trellis, which a) impose an extremely short delay of just N symbols, and b) result in a small number of branch calculations and path memory storage.

2.3 Practical equaliser:

The multiple integration, which is carried out by multiple summations, requires a large number of calculations for each branch. The number of calculations growth exponentially along with the number of ISI/multipath coefficients that are involved. It is shown (see Appendix.1) that the branch weight calculation (Eqs.10,11) can be replaced with a hard decision approach by finding the branch $\hat{b}_n$ that is closest to the average of the re-scattered received signal, hence,

$$\hat{b}_n = \min_{i \in m(n)} \left\{ b_i - \hat{R}_{y_n} \right\} \tag{14}$$

where $m(n)$, the possible indexes of the paths that determinate at time n and,

$$\hat{R}_{y_n} = E\left\{ y_n - \sum_{i=1}^{N} x_{n-i} \cdot ISI \right\} \tag{15}$$

therefore, executing hard decision detection. It is shown by simulation that the degradation in performance is minimal, however the amount of calculation and memory storage size is exponentially slashed.

The equaliser characteristics:

Since the equaliser requires to have just the range of each of the ISI/multipath coefficients, even a wrong output by the trellis equaliser has a smaller error in the sense that while it decides on wrong symbols, these symbols are closer to the transmitted symbols. This characteristic is shown in detail in the simulation.

3. Combined receiver system, adaptive estimation and equalisation

In [2] we presented an ISI/multipath estimator when high-order constellation is used. That estimator uses identified Reliable symbols, and bases its decisions solely on the demodulated data. We present here an adaptive estimator that produces its estimation based on: 1) Initial calculated guess of the ISI/multipath coefficient; 2) The decision made through the equaliser; 3) the reliable symbols inside the received stream data. The estimator uses the LS matrix form for the estimation, similar to the estimator that is presented in [2]. It is important to notice that there are several possible estimation vehicles that can be used, and one does not necessary need to use the LS vehicle, although the LS technique allows achieving optimality in the presence of AWGN.

The estimator feeds the equaliser an initial guess of the ISI/coefficients. The initial guess can be based on: 1) some sort of "a priori" knowledge; or 2) the output of the received constellation point location estimator that produces, as a by-product, the sum of the absolute of the ISI/multipath coefficients, therefore the coefficients can be this sum divided by the length of the ISI/multipath channel; or 3) can be just the all zero N length guess. Based on this guess the equaliser produces its decisions. Unless luckily it guesses the right coefficients, which is not reasonable to expect the equaliser produces mainly wrong decisions on the transmitted symbols. However, since the equaliser has the characteristic, that it decreases the distance between the actual decided symbol and the correct symbol, the output of the equaliser has a smaller error in the sense of the metric distance from the correct symbols. The selected symbol path that the equaliser provides is fed back into the adaptive estimator. The adaptive estimator processes this data through the use of the weighting matrix that increases the weight of the reliable symbols and decreases the weight of the non-reliable symbols. Note that contrary to the estimator which is described in [2], this adaptive estimator uses all available reliable symbols, when it processes the correct path and most of the reliable symbols when processing close to the correct path, and not just those that can be identified by the way that is described in [2]. Thus the number of reliable symbols that are being used in this case is exponentially higher. The second important point, is that the estimator uses the output path of the

equaliser, which becomes closer and closer to the real coefficients, therefore the number of reliable symbols becomes progressively greater and greater. The estimator feeds into the equaliser the new coefficient estimates and thereafter the equaliser new decisions are produced, which are fed back into the adaptive estimator, and so on until the ISI/multipath coefficients are getting steady on the final levels.

References:

[1] E.Riess and L. F. Turner, "The use of 'Reliable Symbols' for Channel Parameter Estimation when using high-order constellations,"

[2] E.Riess and L. F. Turner, "Channel Parameter Estimations Based on the 'Reliable Symbols Method' when High-Order Constellations are used,"

(both included in copending British Patent Application No. 9926167.9)

CLAIMS

1. A method of trellis equalisation, for an ISI/multipath channel when high order constellation communication is used, which comprises the steps of:

1) Identifying an initial "reliable symbol" in the received signal;

2) Setting an initial value for the ISI coefficients;

3) Estimating the sequence of at least N length prior symbols, where N is the selected length of the ISI channel window;

4) Identifying the most likely branch or set of branches of the trellis following the reliable symbol;

5) Using the branch or set of branches to determine the next individual symbol or symbol path and to provide a refined estimate of the ISI coefficients;

6) Moving the channel window forward so as to include a new sequence of N symbols and repeating the process with the new sequence of symbols and the refined estimate of the ISI.

2. A method according to claim 1 in which the initial reliable symbol is identified from a predetermined transmitted training signal.

3. A method according to claim 1 or claim 2 in which a probability weighting for each of a set of branches is calculated from :

$$w_{m,n}^{N} = \left\{ \int_{ISI_0^R} \int_{ISI_1^R} \cdots \int_{ISI_N^R} \frac{1}{\sqrt{2\pi\sigma^2}} e^{-(y_n - \sum_{j=0}^{N} x_{n-j}^{m} \cdot ISI_j)^2 / 2\sigma^2} \, dISI_0 \cdots dISI_N \right\} \qquad (10)$$

in which M is the assumed transmitted symbol path.

4. A method according to claim 1 or claim 2 in which the most likely branch is identified as the one which is closest to the average of the rescattered received signal and using that branch to determine the next individual symbol.

5. A method according to claim 4 in which the branch is identified from

$$\hat{b}_n = \min_{i \in m(n)} \left\{ b_i - \hat{R}_{y_n} \right\} \qquad (14)$$

and

$$\hat{R}_{y_n} = E\left\{ y_n - \sum_{i=1}^{N} x_{n-i} \cdot ISI \right\} \qquad (15)$$

6. A mismatch equaliser using the method of any preceding claim.

7. A receiver system for an ISI channel comprising a mismatch equaliser according to claim 6 and having two inputs, one of which is supplied with the signal from the channel, whilst the other is supplied with ISI/multipath coefficients comprising the output of an adaptive estimator, the input of the adaptive estimator being supplied with output decisions from the equaliser as well as the received signal.

8. A signal communication system including a receiver according to claim 7.

9. A wireless communication system having handsets and/or base stations including a receiver system according to claim 7.

10. A wired communication system including digital subscriber lines (X-DSL) and incorporating receivers according to claim 7.

11. A digital radio/television broadcasting system including receivers according to claim 7.

12. A communication system in which the signal is propagated via coaxial cable and incorporating a receiver system according to claim 7.

13. A communication system in which the signal is propagated via fibre optic link and incorporating a receiver system according to claim 7.

ABSTRACT

"Adaptive Blind Equaliser"

A receiver system for a high order constellation signal carried by an ISI channel, comprising a "mismatch equaliser" having two main inputs, one of which is supplied with the received signal, while the other is supplied with ISI/multipath coefficients. These are provided by the output of an adaptive estimator having one input which is supplied with the received signal and another input which is supplied with output decisions from the equaliser.

PCT/GB 00 / 02634

The Receiver system

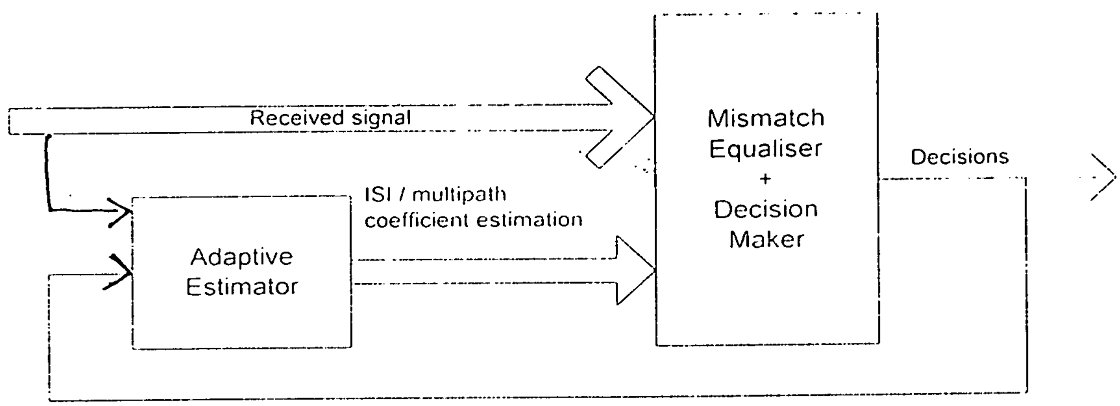


Figure 1

PCT/GB 0 0 / 0 2 6 3 4

Trellis Equalisation and Hard decision

256QAM / 4 coefficients length Multipath channel

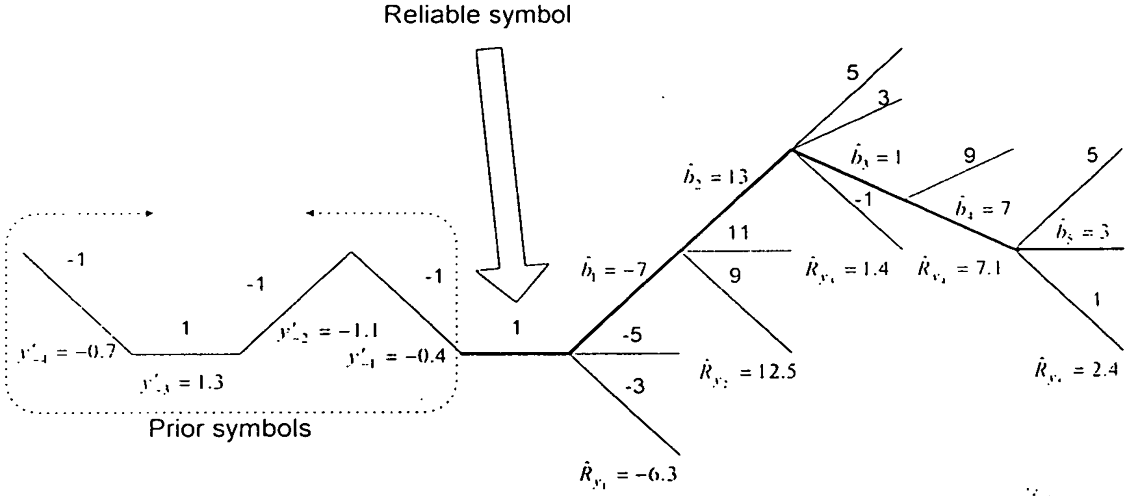


Figure 2